Universal threshold for single-spin asymmetries in fixed target experiments

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Abstract

The analysis of inclusive π-meson single spin asymmetry measurements was done. It was found that the single spin asymmetry starts to grow up at the same value of the π-meson energy in the center of mass system for fixed target experiments at the beam energy range from 13 to 200 GeV.

Polarization experiments give us an unique opportunity to probe the nucleon internal structure. While spin averaged cross-sections can be calculated within acceptable accuracy, current theory of strong interactions can not describe large spin asymmetries and polarization.

Unexpected large values of single spin asymmetry A_N (SSA) in inclusive π-meson production are real challenge to the theory because perturbative Quantum Chromodynamics predicts small asymmetries decreasing with transverse momentum. Various models were developed to explain results from E704 (FNAL), PROZA-M and FODS (both Protvino) and several BNL experiments. Most of the models analyse experimental data in terms of x_{F} and/or p_T. To investigate the dependence of SSA on a secondary meson production angle, the measurements in the reaction $\pi^- + p_\uparrow \to \pi^0 + X$ were carried out at the PROZA-M experiment (Protvino) at 40 GeV pion beam in the two different kinematic regions: at Feinman scaling variable $x_{\mathrm{F}} \approx 0$ [1] and in the polarized target fragmentation region [2]. It was reported [2] that the asymmetry of inclusive π^0 production in the reaction $\pi^- + p_\uparrow \to \pi^0 + X$ starts to grow up at the same centre of mass energy $E_0^{cms} \approx 1.7$ GeV for the both kinematic regions. A similar behaviour was also found in the reaction $p + p_\uparrow \to \pi^0 + X$ at 70 GeV [3]. There is an indication that the asymmeties are zero till some threshold value and then start to rise up linearly and in principle may saturate at some level.

In this case we can fit SSA by the function

$$A_N = \begin{cases} 0 & , \; E < E_0 \\ k \cdot (E - E_0) & , \; E \geq E_0 \end{cases} \tag{1}$$

with two parameters – a threshold energy E_0 and k. Let us mention that π^0-mesons were detected in rather narrow solid angle. In this case the dependence of the asymmetry on energy reflects the dependence on transverse momentum in the central region or on $x_{\rm F}$ in the polarized particle fragmentation region. Saturation, if exists, is achieved at large values of transverse energy or $x_{\rm F}$. The error bars in this region are large and the last measured points are not crucial for the results of a fit. In this case we can neglect by the saturation effect and use all points for fitting by the function (1).

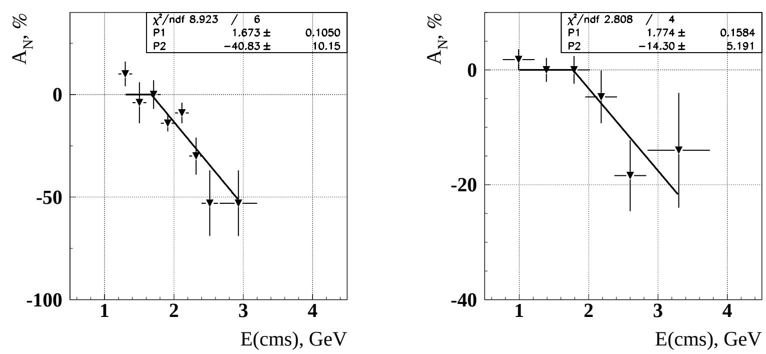

Figure 1: The dependence of A_N on π^0-meson energy in the c.m.s. in the reaction $\pi^- + p_\uparrow \rightarrow \pi^0 + X$ at the central region (left) [1] and in the polarized target fragmentation region (right) [2] at 40 GeV.

The result of this fit is presented in **Fig. 1**. The asymmetry starts to rise up at $E^0_{cms} = (1.67 \pm 0.11)$ GeV in the central region and $E^0_{cms} = (1.76 \pm 0.16)$ GeV in the target fragmentation region. Really the error bars are higher due to energy resolution and averaging over transverse momenta and $x_{\rm F}$. For example, if $x_{\rm F}$ changes by 0.01, this would bring 0.1 GeV dispalcement in the final result at 200 GeV.

Asymmetry in π^+ production.

The result of these two measurements shows that SSA starts to grow up at the same energy. However we can not make a final conclusion whether the SSA behaviour depends on a beam energy or not. We have analysed other experimental data to study this threshold effect.

A comparison of E704 (FNAL) and E925 (BNL) experimental results is presented in **Fig. 2**. The π^+ asymmetry in the E925 experiment (22 GeV,

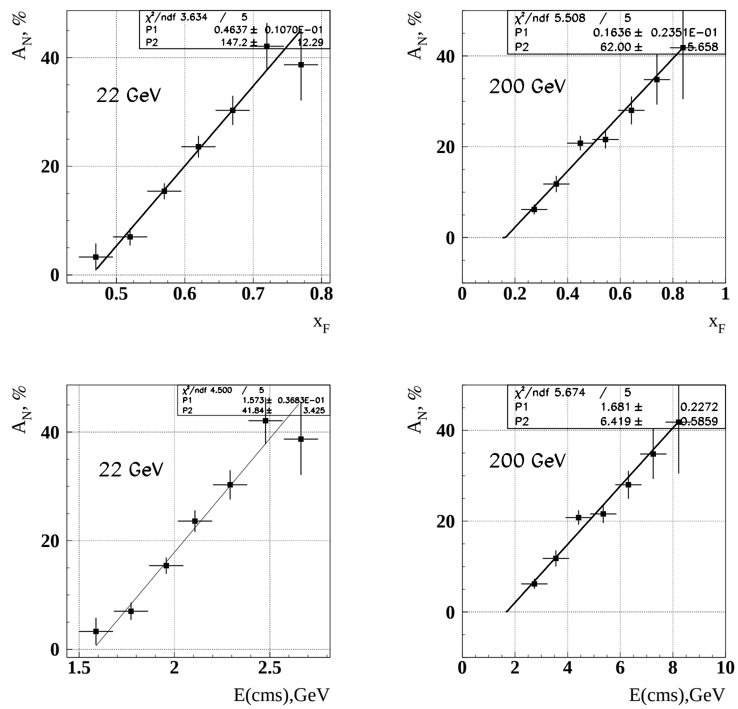

Figure 2: The dependence of A_N on $x_{\rm F}$ (top) and energy in c.m.s. in the reaction $p_\uparrow + p \to \pi^+ + X$ in the polarized beam fragmentation region from the experiments E925 at 22 GeV (left) [4] and E704 at 200 GeV (right) [5]

[4]) and in the E704 experiment (200 GeV, [5]) starts to rise up at different values of $x_{\rm F}$ ($x_{\rm F}^0 \approx 0.18$ for E704 and $x_{\rm F}^0 \approx 0.46$ for E925), but at the same energy in the centre of mass system, $E_0^{cms} \approx 1.6$ GeV. It happened to be surprisingly the same energy as for the PROZA-M experiment.

We used the results of the all fixed target experiments in the energy range between 13 and 200 GeV and fit the asymmetry by the function (1) regardless that in the original papers the asymmetry was presented as a function of p_T or $x_{\rm F}$.

The dependence of the π^+ inclusive production asymmetry on transverse momentum was also studied at BNL at $< x_{\rm F} >= 0.2$ at 13.3 and 18.5 GeV [6] and by the FODS collaboration at Protvino in the central region [7]. The asymmetry starts to rise up at $E_0^{cms} = (1.26 \pm 0.04)$ GeV at the beam energy of 13.3 GeV and at $E_0^{cms} = (1.46 \pm 0.08)$ GeV at 18.5 GeV (see **Fig. 3**).

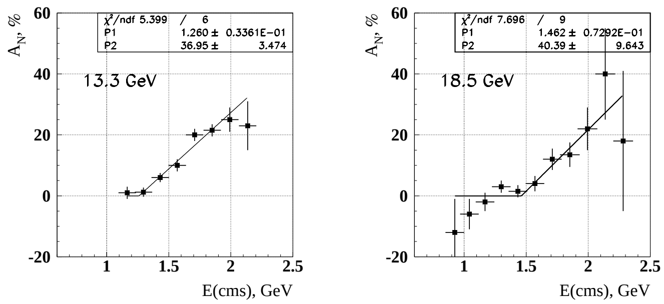

Figure 3: A_N in the reaction $p_\uparrow + p \to \pi^+ + X$ at 13.3 (left) and at 18.8 GeV (right) [6].

The authors [7] claimed that SSA started to rise up at $x_T = p_T/\sqrt{s} = 0.37 \pm 0.02$. This value corresponds to (1.62 ± 0.1) GeV at $x_{\rm F} \equiv 0$. Taking into account the average $x_{\rm F}$ value for each interval we can obtain $E_0^{cms} = (1.64 \pm 0.15)$ GeV.

Asymmetry in π^0 production.

The π^0 inclusive asymmetry was measured in the $pp_\uparrow$-interaction at CERN at 24 GeV [8], in the reaction $\pi^- + p_\uparrow \to \pi^0 + X$ at 40 GeV [2], in the reaction $pp_\uparrow \to \pi^0 + X$ at 70 GeV [3] at Protvino and in the $p_\uparrow p$ and $\bar{p}_\uparrow p$ interactions at 200 GeV at Fermilab [9].

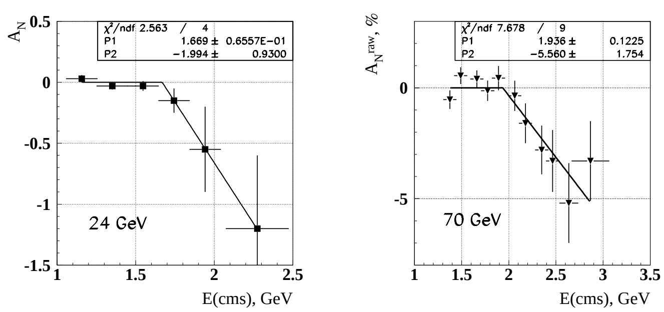

Figure 4: A_N in the reaction $pp_\uparrow \to \pi^0 + X$ in the central region at 24 GeV (CERN [8], left) and in the same reaction in the polarized target fragmentation region at 70 GeV (Protvino [3], right).

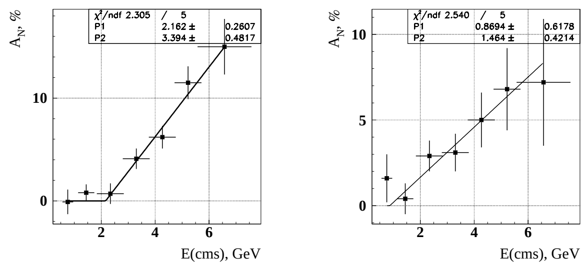

Figure 5: $A_N^{\pi^0}$ in $p_\uparrow p$ (left) and $\bar{p}_\uparrow p$ (right) interactions at 200 GeV

The asymmetry in the reaction $p + p_\uparrow \to \pi^0 + X$ at 24 GeV starts to rise up at $E_0^{cms} = (1.70 \pm 0.07)$ GeV/c and at $E_0^{cms} = (1.93 \pm 0.12)$ GeV at 70 GeV (**Fig. 4**).

A_N in the reaction $p_\uparrow + p \to \pi^0 + X$ at 200 GeV [9] starts to rise up at $E_0^{cms} = (2.16 \pm 0.26)$ GeV, and at $E_0^{cms} = (0.9 \pm 0.6)$ GeV in the reaction $\bar{p}_\uparrow + p \to \pi^0 + X$ in the polarized beam fragmentation region (**Fig. 5**).

The asymmetry in the reaction $p_\uparrow + p \to \pi^0 + X$ in the central region was found to be zero at 70 [10] and 200 GeV [11].

Asymmetry in π^- production.

The SSA in the reaction $p_\uparrow + p \to \pi^- + X$ in the polarized beam fragmentation region starts to grow up at $E_0^{cms} = (1.95 \pm 0.02)$ at 22 Gev [4] and at $E_0^{cms} = (2.9 \pm 0.2)$ at 200 GeV [5] (**Fig. 6**).

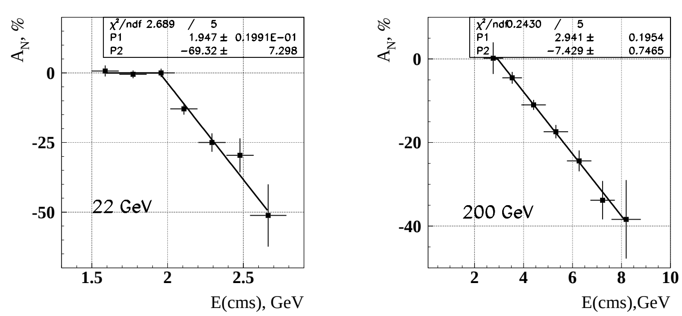

Figure 6: A_N in the reaction $p_\uparrow + p \to \pi^- + X$ in the polarized beam fragmentation region at 22 GeV (left, [4]) and 200 GeV(right, [5]).

The π^- inclusive asymmetry in this reaction in the central region was found to be zero at the experiments carried out at BNL at 13.3 and 18.5 GeV [6] and at Protvino at 40 Gev [7].

Asymmetry in the reaction $\bar{p}_{\uparrow}p \to \pi^{\pm} + X$ at 200 GeV

The SSA in the reaction $\bar{p}_{\uparrow}p \to \pi^{\pm}X$ in the beam fragmentation region was measured at Fermilab at 200 GeV (**Fig. 7**). The asymmetry starts to rise up at $E_0^{cms} = 3.1 \pm 0.5$ for π^+ and at $E_0^{cms} = 1.0 \pm 2.2$ GeV for π^--meson.

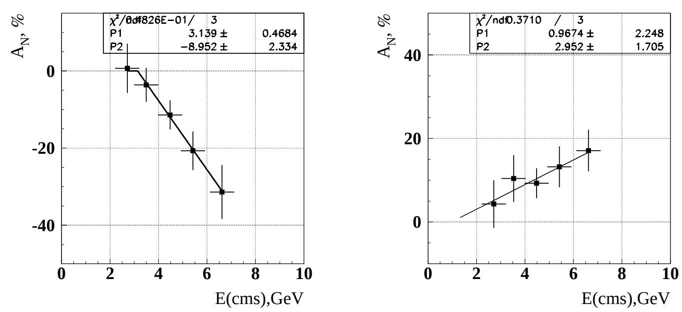

Figure 7: $A_N^{\pi^+}$ (left) and $A_N^{\pi^-}$ (right) in the $\bar{p}_{\uparrow}p$ interaction in the beam fragmentation region at 200 GeV [12].

Discussion.

The combined result of our analysis is presented in **Fig. 8** and **Table 1**. The error bars include both the fit procedure errors and the resolution of kinematic parameters. The values of χ^2/N and the slope of $k \cdot (\sqrt{s} - E^0_{cms})$ (asymptotic asymmetry at the phase space limit whithout saturation effect) are also presented in the table. We did not include the experiments where the asymmetry is close to zero in this table.

The main conclusion is that the asymmetry starts to grow up at the same centre of mass energy $E_0^{cms} = 1.5$ to 2.0 GeV for the most of the experiments in the energy range between 13 and 200 GeV. The analysis was done only for those experimental data where a transverse momentum p_T was greater than 0.5 GeV/c to exclude soft interactions. The conclusion is valid for all π^+ and π^0 asymmetries. We have to mention that π^- production seems to contradict to this. We can explain this fact that π^--meson at

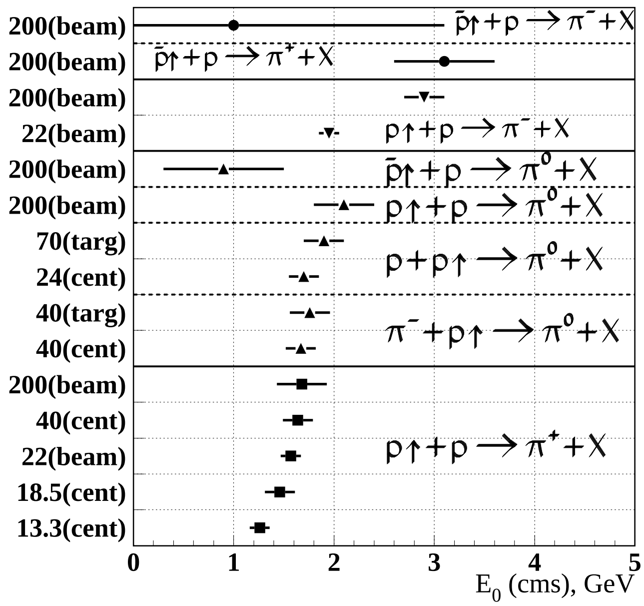

Figure 8: Centre of mass energy values where the pion asymmetry begins to grow up for different experiments. The energy along the Y-axis is in GeV; *cent* – corresponds to experiments in the central region ($x_f \approx 0$), *targ* – the polarized target fragmentation region; *beam* – the polarized beam fragmentation region.

small x_F can be produced not only from the valence d-quark but also from other channels. The interference of different channels is also responsible for asymmetry cancellation in π^0 and π^- production in the central region. In the reaction $\pi^- + p_\uparrow \rightarrow \pi^0 + X$ in the central region we found significant asymmetry in the contrary to the $p_\uparrow + p \rightarrow \pi^0 + X$ reaction. If in the $p_\uparrow + p \rightarrow \pi^0 + X$ reaction the asymmetry is cancelled because of different channel interference from a polarized and non-polarized proton, in the $\pi^- p_\uparrow$ collisions the valence u-quark from a polarized proton combining with the valence $\bar{u}$-quark from π^- gives the main contribution to π^0 production, while other channels are suppressed.

In this scheme the asymmetry behaviour in $\bar{p}_\uparrow p$ interactions in π^+ and π^-

Table 1: Summary table. Centre of mass energy values E^0_{cms} where the pion asymmetry begins to grow up for different experiments. $E^{max}_{cms} = \sqrt{s}/2$.

Reaction	Energy	E^0_{cms}, GeV	χ^2/N	$k \cdot (E^{max}_{cms} - E^0_{cms})$, %	Ref.
$p_\uparrow + p \to \pi^+ + X$	13.3	1.26 ± 0.1	0.9	52 ± 6	[6]
$p_\uparrow + p \to \pi^+ + X$	18.5	1.46 ± 0.15	0.85	63 ± 16	[6]
$p_\uparrow + p \to \pi^+ + X$	21.92	1.57 ± 0.1	0.9	68 ± 6	[4]
$p_\uparrow + p \to \pi^+ + X$	40	1.64 ± 0.15			[7]
$p_\uparrow + p \to \pi^+ + X$	200	1.68 ± 0.25	1.1	52 ± 5	[5]
$\pi^- + p_\uparrow \to \pi^0 + X$	40	1.67 ± 0.15	1.5	107 ± 26	[1]
$\pi^- + p_\uparrow \to \pi^0 + X$	40	1.76 ± 0.2	0.7	36 ± 14	[2]
$p + p_\uparrow \to \pi^0 + X$	24	1.7 ± 0.15	0.6	334 ± 165	[8]
$p + p_\uparrow \to \pi^0 + X$	70	1.9 ± 0.2	0.85	208 ± 70	[3]
$p_\uparrow + p \to \pi^0 + X$	200	2.1 ± 0.3	0.5	26 ± 5	[9]
$\bar{p}_\uparrow + p \to \pi^0 + X$	200	0.9 ± 0.6	0.5	13 ± 4	[9]
$p_\uparrow + p \to \pi^- + X$	21.92	1.95 ± 0.1	0.5	87 ± 11	[4]
$p_\uparrow + p \to \pi^- + X$	200	2.9 ± 0.2	<0.1	51 ± 6	[5]
$\bar{p}_\uparrow + p \to \pi^+ + X$	200	3.1 ± 0.5	<0.1	59 ± 16	[12]
$\bar{p}_\uparrow + p \to \pi^- + X$	200	1.0 ± 2.2	0.1	25 ± 15	[12]

production should be inversed in comparison with the $p_\uparrow + p \to \pi^0 + X$ data. The result from E704 experiment [12] is consistent with this model. The asymmetry of π^+-production starts to grow up at the same value $E_0^{cms} \approx$ 2.9 GeV as for π^- in reaction $p_\uparrow + p \to \pi^0 + X$, and the asymmetry in the reaction $\bar{p}_\uparrow + p \to \pi^- + X$ begins to rise up at small value E^0_{cms}.

We can conclude that the meson asymmetry produced by valence quark starts to grow up at the same universal energy E^0_{cms}. Also the values of the parameter $k \cdot (E^{max}_{cms} - E^0_{cms})$ are close for all eight measurements in the reactions $p_\uparrow + p \to \pi^+ + X$ and $p_\uparrow + p \to \pi^- + X$.

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